Effects of Cutting Date, Outdoor Storage Conditions, and Splitting on Survival of *Agrilus planipennis* (Coleoptera: Buprestidae) in Firewood Logs

TOBY R. PETRICE AND ROBERT A. HAACK

USDA–Forest Service, North Central Research Station, 1407 S. Harrison Road, Michigan State University, East Lansing, MI 48823

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ABSTRACT The emerald ash borer *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae) is an exotic pest of ash (*Fraxinus* spp.) in North America. We conducted studies in Michigan to evaluate how different tree cutting dates, outdoor storage conditions, and splitting affected *A. planipennis* survival in firewood logs. In 2002–2003, we cut logs from *A. planipennis*-infested ash trees each month, from July to October, and stored half of the logs in shade and half in full sun. In 2003–2004, we tested logs cut July–December; stored in sun versus shade; tarped versus untarped; and whole logs versus split logs. For both years, *A. planipennis* successfully emerged the summer after cutting from logs that represented all treatments and all cutting dates tested. Adult emergence density was significantly lower in logs cut in July and August. In 2003–2004, *A. planipennis* adult length was significantly shorter, and percentage of mortality was significantly higher for logs cut in August compared with later months. Emergence density was significantly lower for split logs compared with whole logs for all cutting months except for December. There was no significant difference in adult emergence density between logs stored in full sun versus shade in 2002–2003. In 2003–2004, untarped logs in full sun or shade had significantly lower adult emergence densities than tarped logs in the sun or shade. In conclusion, emergence, survival, and size of *A. planipennis* was significantly reduced if logs were cut early during larval development (July or August); splitting logs and storing them untarped in full sun or shade further reduced adult emergence. No treatment was 100% effective in preventing adult emergence.

KEY WORDS *Agrilus planipennis*, emerald ash borer, Buprestidae, cultural control, invasive non-native pest

The emerald ash borer *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae) was first discovered in North America in southeastern Michigan in June 2002, and within 1 mo it also was found in neighboring Windsor, Ontario, Canada (Haack et al. 2002). Surveys conducted in 2002 found this beetle in six counties in southeastern Michigan and one county in Ontario. As of February 2006, *A. planipennis*-quarantined areas include 21 counties and 31 outlier sites in Michigan, 11 counties or parts of in Ohio, six in Indiana, and three in Ontario; many of these new infestations were a result of inadvertent human-assisted movement of infested ash firewood or nursery stock.

Recently, Jendek (1994) synonymized three species and one subspecies of Asian *Agrilus* under the name *A. planipennis*. *A. planipennis* is native to China, Korea, and Japan as well as parts of Mongolia, eastern Russia, and Taiwan (Yu 1992, Jendek 1994, Liu et al. 2003). Ash (*Fraxinus* spp.) is the only known host of *A. planipennis* in China; in addition to ash, elm (*Ulmus* spp.), walnut (*Juglans* spp.), and wingnut (*Pterocarya* spp.) are listed as *A. planipennis* hosts in Japan; and elm is the only reported host of *A. planipennis* in Korea (Chinese Academy of Science, Institute of Zoology 1986, Yu 1992, Akiyama and Ohmomo 1997, Sugiura 1999, Xu 2003). To date, ash is the only known host of *A. planipennis* in North America (Haack et al. 2002, Liu et al. 2003, Cappaert et al. 2005).

A. planipennis generally has a 1-yr life cycle, although some individuals may require 2 yr to complete development (Yu 1992, Cappaert et al. 2005). In Michigan, adults emerge from May through August with peak emergence occurring in June or July. Adults feed on foliage for 1 to 2 wk before mating and females begin laying eggs on the bark surface of live ash trees. Larvae hatch from eggs in 2 to 3 wk (24°C) and tunnel through the bark to the cambial region. Larvae develop through four instars during the summer and then tunnel into the sapwood or outer bark where they construct pupal cells and overwinter as prepupae. Pupation occurs the next spring or summer and generally lasts 2 to 3 wk (24°C). Adults form and emerge through the bark within another 1 to 2 wk. Most *A. planipennis* larvae in North America overwinter as prepupae or fourth instars; however, we have found first, second, and third instars during winter.

Table 1. Summary data for green and white ash trees cut into firewood logs in Michigan in 2002 and 2003, including year and month of cutting, location, number of trees, mean diameter at breast height (dbh), mean ± SE number of *A. planipennis* larvae per square meter of bark surface area, and percentage of *A. planipennis* larval instar distribution at time of cutting

Yr and mo cut	Location	No. trees	Mean dbh	Mean no. larvae/m²	Mean larval distribution (%)			
					First	Second	Third	Fourth[a]
2002								
July	Northville	3	19.9 ± 6.9	23.2 ± 7.2	26	31	7	36
Aug.	Livonia	4	22.6 ± 0.7	158.0 ± 42.7	3	6	25	66
Sept.	Livonia	5	20.3 ± 3.5	88.5 ± 18.0	0	1	7	92
Oct.	Livonia & Northville	3	23.7 ± 5.2	73.1 ± 17.4	0	1	2	97
2003								
July	Novi	4	15.3 ± 1.3	16.7 ± 6.8	39	0	0	61
Aug.	Novi	7	16.0 ± 1.9	270.7 ± 52.3	24	23	35	18
Sept.	Novi	12	16.6 ± 1.6	106.7 ± 17.6	1	17	29	53
Oct.	Ann Arbor and Novi	3	21.6 ± 3.6	102.1 ± 31.7	3	25	10	62
Dec.	Ann Arbor and Novi	5	18.4 ± 2.7	106.4 ± 16.9	0	6	23	71

[a] Includes larvae that were still feeding and larvae that had completed feeding, i.e., prepupae.

A. planipennis is one of the most significant exotic pests to be introduced into North America in recent years, given that it has already killed millions of ash trees in Michigan alone (Liu et al. 2003, Cappaert et al. 2005). Large volumes of *A. planipennis*-infested ash wood have accumulated from tree removal programs for *A. planipennis*-killed trees, ash reduction efforts within the *A. planipennis* quarantined areas, and eradication of *A. planipennis* populations outside the quarantined areas. A common use of infested wood is as firewood. Also, some of the merchantable ash logs are being processed into products such as lumber and tool handles. However, because *A. planipennis* can survive and emerge from logs cut from infested trees, movement of all ash logs from infested counties to uninfested counties is regulated by the current federal quarantine (USDA–APHIS 2003). In addition, movement of firewood from all hardwood species is regulated. The currently accepted disposal method of ash logs, to ensure mortality of *A. planipennis* life stages, is to grind wood into 2.54-cm (1-in.) or smaller pieces (USDA–APHIS 2003). However, because of the overwhelming volumes, not all wood can be disposed of in this manner.

Previous studies have found that tree cutting date and storage methods can affect survival of *Agrilus* species in cut wood (Anderson 1944; Dunbar and Stephens 1974; Haack and Benjamin 1980). In 2002–2005, we conducted a study to determine the effects of cutting date, outdoor storage conditions, and splitting on *A. planipennis* survival and adult emergence in firewood cut from infested trees.

Materials and Methods

2002–2003 Study. In 2002, we cut firewood-length (≈40-cm-long) logs 2–4 times each month, during July through October in the cities of Livonia, Wayne County, and Northville, Oakland County, MI, located within the main *A. planipennis*-infested area in southeastern Michigan (Table 1). An average of 20 logs were cut each month from heavily infested green ash, *Fraxinus pennsylvanica* Marsh, and white ash, *Fraxinus americana* L., trees. Firewood log diameters ranged from 6 to 37 cm and averaged 15 cm. All *A. planipennis* exit holes already present on the logs were filled with white caulk so they would not be confused with any new exit holes created by *A. planipennis* that emerged the next year of the study. One half of the logs cut each month were stored in full sunlight in a mowed field and the other half in the shade under a hardwood forest canopy that was ≈75% shaded when foliage was present. Logs were layered on top of one another in large stacks. The bottom layer of logs was elevated ≈10 cm above the ground on pieces of lumber to avoid direct contact with the soil. After adult emergence was completed in August 2003, we recorded length, diameter, and number of new *A. planipennis* exit holes for each log. The number of new exit holes per square meter of bark surface area was calculated for each log.

When each tree was cut, we also dissected a subset of logs along its length to estimate larval densities and development for each cutting date. Larvae extracted from each log were preserved in 70% ethyl alcohol, and later their urogomphi were measured with a dissecting microscope to determine instar.

2003–2004 Study. In 2003, firewood-length (40-cm-long) logs were cut from green ash trees one to two times per month from July through October and once in December (Table 1). We cut heavily infested trees at two locations in southeastern Michigan: Novi, Oakland County, and Ann Arbor, Washtenaw County (Table 1). Log diameters ranged from 5 to 37 cm and averaged 10 cm. A portion of the logs from each cutting date were split lengthwise into smaller pieces where the remaining bark circumference averaged 13.1 ± 0.2 cm (mean ± SE). All old exit holes were caulked shortly after cutting as described above. Similar sized logs were distributed evenly among the following storage treatments: full sun, full sun and tarped, shade, and shade and tarped. Each treatment received an average of 30 whole and 22 split logs each month. Logs in the full sun treatments were stored in a mowed field where they received direct sunlight throughout the day. Logs in the shade treatments were stored in a nearby hardwood forest that received ≈75% shade when foliage was present. For the tarped treatments, we used a 10-mil weight blue tarp with the edges of the tarp secured to the ground with stakes. Logs were layered on top of one another in large stacks. The bottom layer of logs in each stack was elevated ≈10 cm above the ground on pieces of lumber. Metal posts were driven into the ground at each end of the log stacks to prevent them from collapsing.

We selected a log from the lower, middle, and upper bole of each cut tree to obtain baseline information on *A. planipennis* density and life stages present at the time of cutting. These logs were generally dissected within 1 to 2 d of cutting or were stored in a cool room at 6°C until dissection could be performed. *A. planipennis* larval densities were recorded for each log. Larvae extracted from each log were preserved in 70% ethyl alcohol, and their urogomphi were later measured under a dissecting microscope to determine average larval instar for each month trees were cut.

On 15 December 2003, we selected three to six whole logs and three to six split logs from each month of cutting and storage treatment combination to rear in the laboratory and evaluate *A. planipennis* survival. Logs were placed in cardboard rearing tubes with plastic caps on each end. We cut a 15-cm-diameter hole in one of the plastic caps of each rearing tube and covered the hole with vinyl hardware cloth for ventilation. In the center of the screen, we cut a 7.5-cm-diameter hole and attached a plastic lid that accepted a screw-on plastic cup to collect emerging adults. Vinyl screening and plastic lids were attached using adhesive caulk. Laboratory temperatures were ≈24°C. Emerged adults were collected every 2 d, counted, and frozen. Adults were sexed and their length was measured dorsally from the front of the head to end of abdomen. After adult emergence was complete in the laboratory, all logs were dissected to assess larval mortality, and percentage of mortality was calculated [(no. dead *A. planipennis* larvae, pupae, and adults per log) ÷ (no. adult *A. planipennis* that emerged per log + no. dead *A. planipennis* larvae, pupae, and adults per log) × 100]. Also, instar determination was made on a subset of dead larvae from each log and compared with average instar at the time the trees were cut.

We left the remaining logs in the field to allow adults to "naturally" emerge during summer 2004. In late May 2004, before adult emergence, we unstacked all logs and stood them on their cut ends to ensure that emerging adults could easily exit all logs. Tarps were replaced as necessary. In late August 2004, after adult emergence was complete, we recorded the length, diameter, and the number of new exit holes present on each log.

2005 Study. After reviewing the results of the previous two studies, we became interested in how air temperature varied within the firewood stacks for the different storage treatments as well as how tarp color would affect temperature. In February 2005, we restacked logs from the 2003–2004 study in their original treatment stacks. In each of the four treatment stacks, we placed a HOBO Pro temperature data recorder (Onset, Pocasset, MA). Temperature sensors were placed on the top and in the center of each stack and data were recorded from 3 to 23 February and from 30 March to 22 April 2005. Three HOBO Pro relative humidity data recorders were rotated among the four treatments. Relative humidity was recorded for sun, shade, and shade-tarped treatments for the period of 10–29 March; and for sun, sun-tarped, and shade-tarped treatments for the period of 30 March–22 April 2005.

On 3 February 2005, firewood-length logs were cut from two *A. planipennis*-infested green ash trees. Several discs (with bark attached) were cut from each tree, weighed, dried, and weighed again to determine percentage of moisture content. We placed three to five logs from the trees in each of the four treatment stacks. On 22 April 2005, discs were cut from the center of each log, weighed, dried, and weighed again to determine percentage of moisture content.

We also compared the effect of different colored tarps on temperatures within the firewood stacks. Firewood stacks were constructed at the same location where logs were stacked for 2003–2004 sun treatments and covered with one of the following: blue tarp (10-mil weight), clear tarp (10 mil), black tarp (30 mil), or no tarp. Tarps were secured to the ground and temperatures were recorded on the top and in the center of each firewood stack from 22 April to 1 June 2005.

Statistical Analyses. *A. planipennis* exit holes per square meter of log surface area, percentage of *A. planipennis* mortality, and *A. planipennis* adult lengths were compared among treatments with a mixed model analysis of variance (ANOVA) (PROC MIXED, SAS Institute 2001). December data were not included in the percentage of mortality and adult length analyses, because the subset of logs selected from the log stacks for these two data sets were brought into the laboratory for rearing at the same time that the December logs were cut. Therefore, logs cut in December were not subjected to the outdoor storage conditions as were the logs cut in earlier months. July data were excluded from the percentage of mortality analysis, and July data and split-log data were excluded from adult length analyses because the sample sizes were too small. Arcsine square-root transformation was performed on percentage data, and square-root transformation was performed on exit hole density and adult length data before analyses. Means that were significantly different at the $P < 0.05$ level were separated using the Tukey–Kramer method for pairwise comparisons.

Mean instar at the time of cutting was compared with mean instar of the dead larvae found during dissection of the logs after adult emergence had ended in the laboratory by using ANOVA (PROC GLM, SAS Institute 2001). Means that were significantly different at the $P < 0.05$ level were separated using Dunnett's one-tailed *t*-test. We set the mean instar at the time of cutting as the control to determine whether larvae continued to develop after trees were cut.

Temperature, humidity, and percentage of moisture content were analyzed using one-way ANOVA (PROC GLM, SAS Institute 2001). Means that were significantly different at the $P < 0.05$ level were separated using the Tukey–Kramer method for pairwise comparisons.

Table 2. Mixed model ANOVA results for various life history parameters in 2002–2003 and 2003–3004 in firewood logs cut from ash trees in Michigan during different months, stored under different outdoor conditions, and left whole or split

Source	df[a]	F	P
2002–2003 Exit holes/m^2 surface area[a]			
Storage condition	1, 71	2.05	0.1567
Mo	3, 71	7.71	0.0002
Storage condition × split	3, 71	1.12	0.3455
2003–2004 Exit holes/m^2 surface area[b]			
Storage condition	3, 1,024	8.49	<0.0001
Mo	4, 1,024	72.18	<0.0001
Storage condition × mo	12, 1,024	0.74	0.7134
Split	1, 1,024	63.31	<0.0001
Storage condition × split	3, 1,024	0.37	0.7765
Mo × split	4, 1,024	6.51	<0.0001
Storage condition × mo × split	12, 1,024	0.66	0.7946
2003–2004 % mortality[c,d]			
Storage condition	3, 79	1.03	0.3823
Mo	2, 79	3.19	0.0465
Storage condition × mo	6, 79	1.24	0.2948
Split	1, 79	12.46	0.0007
Mo × split	2, 79	0.04	0.9635
Storage condition × split	3, 79	1.11	0.3492
Storage condition × mo × split	6, 79	2.02	0.0730
2003–2004 Adult length[b,d,e]			
Month	2, 33	3.63	0.3650
Storage condition	3, 33	0.44	0.7228
Storage condition × mo	6, 33	0.57	0.7491
Sex	1, 22	12.60	0.0018
Mo × sex	2, 22	0.23	0.7998
Storage condition × sex	3, 22	1.17	0.3429
Mo × storage condition × sex	6, 22	2.16	0.0864

[a] Degrees of freedom numerator, denominator.
[b] Analysis performed on square root-transformed data.
[c] Analysis performed on arcsine square root-transformed data.
[d] Logs cut in July and December 2003 not included in this analysis (see text).
[e] Split logs not included in this analysis (see text).

Results

2002–2003 Study. Adults successfully emerged from logs cut in all months and from logs stored in both full sun and shade. Mean density of new *A. planipennis* exit holes varied significantly among months logs were cut; logs cut in July had the lowest densities, whereas logs cut in October had the highest densities (Tables 2 and 3). Mean exit hole density did not vary significantly between the full sun and shade storage treatments (Tables 2 and 4).

2003–2004 Study. *A. planipennis* adults successfully emerged from both split and whole logs cut during all months and stored under all conditions (Tables 3 and 4). Overall, mean *A. planipennis* exit hole density was significantly (Table 2) lower in split logs (30.4 ± 2.6 per m^2) compared with whole logs (53.3 ± 2.6 per m^2). Mean exit hole density varied significantly among months logs were cut, and there was a significant interaction between month of cutting and splitting (Tables 2 and 3). Whole and split logs cut in July and August and split logs cut in September and October had the lowest exit hole densities (Table 3). Whole and split logs cut in December and whole logs cut in October and September had the highest exit hole densities (Table 3). Mean exit hole density varied significantly among storage treatments with the lowest

Table 4. Mean ± SE *A. planipennis* adult emergence density (exits per m^2 of log surface area) for 2002–2003 and 2003–2004 and percentage of *A. planipennis* mortality in 2003–2004 by outdoor storage treatment for firewood logs cut from ash trees in July–October 2002 and July–December 2003 in Michigan

Storage treatment	2002–2003	2003–2004	
	Exit holes/m^2 surface area[a]	Exit holes/m^2 surface area[a]	% mortality[b]
Shade and tarped	—[c]	55.7 ± 4.5a	73.7 ± 4.5a
Sun and tarped	—[c]	51.5 ± 4.5a	83.0 ± 5.0a
Shade	53.8 ± 9.1a[d]	34.5 ± 3.3b	80.7 ± 3.6a
Sun	44.0 ± 8.5a	36.3 ± 3.0b	84.6 ± 4.2a

Data were pooled for all months of cutting.
[a] Square root transformations performed on data before analysis (actual means shown).
[b] % mortality = [(total dead ÷ total alive and dead) × 100]; arcsine square root transformations performed on data before analysis (actual means shown).
[c] Not tested in 2002–2003.
[d] Means followed by the same letter (within columns) are not significantly different at the $P \leq 0.05$ level (PROC Mixed; Tukey Tukey–Kramer; [SAS Institute 2001]).

Table 3. Mean ± SE *A. planipennis* adult emergence density (exit holes/m^2 of log surface area) for 2002–2003 and 2003–2004 and percentage *A. planipennis* mortality in 2003–2004 by month of cutting for firewood logs cut from ash trees in July–October 2002 and July–December 2003 in Michigan

Mo cut	2002–2003	2003–2004		
	Exit holes/m^2 surface area[a]	Exit holes/m^2 surface area[a]		% mortality[b]
	Whole logs	Whole logs	Split logs	
July	19.1 ± 5.2c[c]	9.3 ± 2.6bcd	4.1 ± 1.7d	—[d]
Aug.	25.9 ± 4.3bc	29.0 ± 4.7b	6.1 ± 2.2cd	87.3 ± 3.3a
Sept.	70.4 ± 13.7ab	60.7 ± 5.0a	24.9 ± 4.4b	77.7 ± 3.8b
Oct.	90.6 ± 17.0a	68.3 ± 7.7a	32.0 ± 8.4bc	73.8 ± 3.8b
Dec.	—[e]	78.0 ± 5.3a	75.0 ± 6.6a	—[d]

Data were pooled for all outdoor storage treatments.
[a] Square root transformations performed on data before analysis (actual means shown).
[b] % mortality = [(total dead ÷ total alive and dead) × 100]; arcsine square root transformations performed on data before analysis (actual means shown).
[c] Means followed by the same letter (within 2002–2003 exits holes/m^2, 2003–2004 exit holes/m^2, or % mortality) are not significantly different at the $P \leq 0.05$ level (PROC Mixed, Tukey–Kramer; [SAS Institute 2001]).
[d] Sample size too small to include in analysis.
[e] Not tested in 2002–2003.

Table 5. Mean ± SE larval instars of live *A. planipennis* at the time of tree cutting in 2003 and mean larval instar of dead *A. planipennis* remaining after adult emergence was completed for laboratory reared whole logs and split logs cut from ash trees in Michigan

Mo of cutting	Mean larval instar			
	Initial dissection	Post emergence: Whole logs	Post emergence: Split logs	*F*; df; *P*
July	1.95 ± 0.17b[a]	2.66 ± 0.08a	2.52 ± 0.24a	8.9; 2, 202; 0.0002
Aug.	2.56 ± 0.04b	3.32 ± 0.04a	3.23 ± 0.06a	94.7; 2, 1000; 0.0001
Sept.	3.40 ± 0.05b	3.80 ± 0.03a	3.76 ± 0.05a	26.6; 2, 557; 0.0001
Oct.	3.48 ± 0.06a	3.63 ± 0.06a	3.59 ± 0.13a	1.4; 2, 277; 0.2410
Dec.	3.31 ± 0.05b	3.69 ± 0.10a	No data	9.1; 1, 195; 0.0029

[a] Postemergence means followed by the same letter as the initial dissection means (within rows) are not significantly larger than initial dissection means at the $P \leq 0.05$ level (PROC GLM; Dunnett's one-tailed *t*-test; [SAS Institute 2001]).

Table 7. Mean ± SE daily maximum temperatures (°C) recorded from the top and center of ash firewood log stacks covered with different colored tarps or no tarp during the periods of 22 April–1 June 2005

Treatment	Mean daily max temp (°C): Top	Mean daily max temp (°C): Center
Clear tarp	46.4 ± 2.5a[a]	27.5 ± 1.3a
Black tarp	36.5 ± 2.1b	Nd[b]
Blue tarp	36.2 ± 2.1b	19.6 ± 1.0b
No tarp	23.2 ± 1.3c	16.2 ± 1.0b
ANOVA results		
F	21.71	26.8
df	3, 163	2, 122
P	0.0001	0.0001

[a] Means followed by the same letter (within columns) are not significantly different at the $P < 0.05$ level (PROC GLM; Tukey–Kramer; [SAS Institute 2001]).
[b] Nd, temperature probe malfunctioned.

densities found for logs in the untarped full sun and shade treatments (Tables 2 and 4).

Percentage of *A. planipennis* mortality varied significantly between whole (72.4 ± 3.2%) and split logs (89.3 ± 2.4%) and among cutting months (Table 2). Percentage of mortality was highest for logs cut in August, compared with logs cut in September and October (Table 3). Percentage of mortality did not vary significantly among storage treatments (Tables 2 and 4).

The mean instar of dead *A. planipennis* larvae for whole and split logs after adult emergence was completed for laboratory reared logs was significantly higher than mean instar of live larvae at the time trees were cut in 2003 for all months except October, indicating that larvae that failed to complete development in cut logs continued to develop before eventually dying (Table 5).

Mean length (millimeters) of *A. planipennis* adults that emerged from whole logs varied significantly between sexes and among months trees were cut (Table 2). Adults that emerged were shortest for logs cut in August (males, 9.6 ± 0.4; females, 10.1 ± 0.4), intermediate for logs cut in September (10.4 ± 0.2; 11.2 ± 0.3), and longest for logs cut in October (10.8 ± 0.2; 11.4 ± 0.4). Mean length of *A. planipennis* adults did not vary significantly among storage treatments (Table 2; means not shown).

2005 Study. Maximum and minimum temperatures measured at the top and center of log stacks varied significantly among all treatments for both sample periods (Table 6). Maximum temperatures at the top of log stacks were consistently highest for the log stack in full sun and tarped. Minimum temperatures were consistently lowest for the log stacks in full sun and shade that were not tarped. Temperatures at the center of log stacks followed a similar trend, but they varied less among treatments. As expected, temperature extremes were greatest on the top surface compared with the center of the log stacks.

Mean daily maximum temperatures varied significantly beneath tarps of different colors (Table 7). Mean daily maximum temperatures were highest on the top and in the center of the firewood stack covered with a clear tarp, compared with stacks covered with a blue tarp, a black tarp, or no tarp.

Mean relative humidity varied significantly among storage treatments for both sample periods (Table 8). Mean relative humidity was highest for the tarped logs and lowest for the untarped logs. Similarly, mean percentage of moisture varied significantly among treatments (Table 8). Tarped logs and the control logs (moisture measured at time of cutting) had the highest percentage of moisture compared with the untarped logs.

Table 6. Mean ± SE daily maximum and minimum air temperatures (°C) recorded from the top surface and in the center of ash firewood log stacks by storage treatment during the periods of 3–23 February and 30 March–22 April 2005

Treatment	Top surface of firewood stack				Center of firewood stack			
	3–23 Feb.		30 Mar.-22 April		3–23 Feb.		30 Mar.-22 April	
	Max	Min.	Max	Min.	Max	Min.	Max	Min.
Sun and tarped	9.8 ± 2.0a[a]	−2.7 ± 0.6ab	32.8 ± 1.6a	7.0 ± 0.7a	1.1 ± 0.4a	−1.3 ± 0.3a	20.9 ± 1.0a	7.5 ± 0.5a
Shade and tarped	2.2 ± 0.6b	−2.1 ± 0.4a	23.1 ± 1.2bc	6.7 ± 0.6a	−0.6 ± 0.2a	−1.6 ± 0.2a	13.6 ± 0.8c	5.7 ± 0.6a
Sun	3.8 ± 1.0b	−7.1 ± 1.4c	25.1 ± 1.4b	−1.8 ± 0.8c	1.1 ± 0.7a	−4.9 ± 1.0b	18.1 ± 1.0ab	2.7 ± 0.6b
Shade	1.8 ± 0.9b	−6.1 ± 1.2bc	19.9 ± 1.2c	1.0 ± 0.6b	−0.3 ± 0.6a	−5.4 ± 0.9b	16.4 ± 0.9bc	2.4 ± 0.5b
Ambient air			18.9 ± 1.1c	1.7 ± 0.5b			18.9 ± 1.1ab	1.7 ± 0.5b
F	9.02	6.07	18.17	32.89	3.21	9.58	8.23	20.79
df	3, 76	3, 76	4, 124	4, 124	3, 75	3, 75	4, 124	4, 124
P	0.0001	0.0010	0.0001	0.0001	0.0279	0.0001	0.0001	0.001

Means followed by the same letter (within columns) are not significantly different at the $P < 0.05$ level (PROC GLM; Tukey–Kramer; [SAS Institute 2001]).

Table 8. Mean ± SE percentage of moisture content of logs after they were stacked outdoors from 2 February–22 April 2005, and mean ± SE daily relative humidity (%) in the center of stacks for the periods of 10–29 March and 30 March–22 April 2005 by storage treatment

Treatment	% moisture content	Relative humidity (%)	
		10–29 Mar.	30 Mar.–22 April
At time of cutting[a]	28.8 ± 0.6ab[a,b,c]		
Sun and tarped	27.6 ± 0.6b	—[d]	97.5 ± 0.4b
Shade and tarped	30.4 ± 0.4a	99.7 ± 0.1a	100.0 ± 0.0a
Sun	23.7 ± 0.3c	77.1 ± 1.6b	60.0 ± 2.3c
Shade	23.1 ± 0.5c	81.1 ± 1.4b	—[d]
F; df; *P*	39.63; 4, 24; 0.0001	215.36; 2, 62; 0.0001	488.83; 2, 74; 0.0001

[a] Percentage of moisture at the time trees were cut, i.e., 2 February 2005.

[b] Means followed by the same letter (within columns) are not significantly different at the $P < 0.05$ level (PROC GLM; Tukey–Kramer; [SAS Institute 2001]).

[c] Arcsine square root transformations performed on data before analysis (actual means shown).

[d] Only three relative humidity data recorders available for the study.

Discussion

Cutting early (July and August) during larval development significantly reduced *A. planipennis* survival and eventual adult length. The low larval densities in the July-cut logs (Table 1) probably reflects that many *A. planipennis* brood were still eggs on the bark surface or first instars that had not yet reached the cambial region at the time of cutting and dissection. Although survival was reduced, *A. planipennis* emergence still did occur in some July-cut logs in both years. The initial July dissections found a high percentage of late instars still feeding in the phloem (Table 1). These larger larvae represent brood from the previous year that will transform to adults and emerge later in the year of cutting or the next year. Protracted larval development may reflect poor host nutrition, strong host resistance (Haack and Slansky 1987), or late-season oviposition. It is likely that the larger larvae represent the bulk of the individuals that successfully emerged from logs cut in July. Previous studies of native *Agrilus* reported similar findings where larvae in trees cut in summer that were first or second instar died, and larvae that were third or fourth instar usually completed development and emerged as adults (Anderson 1944; Haack and Benjamin 1980).

The high *A. planipennis* mortality in logs cut in August probably reflected a combination of reduced host quality because of drying and intraspecific competition resulting from high larval densities (Table 1). That *A. planipennis* emergence was not significantly lowered in whole logs cut in September or later suggests that larval development was too far advanced to be affected by changes in host quality as a result of felling. There is often a gradual decrease in moisture content and nutritional quality of the phloem after logs are cut (Haack and Slansky 1987). The smaller adult size in August cut-logs compared with September- and October-cut logs also indicated how changes in host quality that occurred early in larval development had a greater negative impact on larval growth when host quality declines later in development.

Apparently, splitting logs accelerated the reduction in moisture content and nutritional quality in logs, given that *A. planipennis* emergence density was significantly lower for split logs compared with whole logs through the cutting month of October. Some larvae may have been injured or killed by mechanical damage during the splitting process, but we feel this was of secondary importance to changes in host quality. Emergence density was not significantly reduced by splitting in December-cut logs, probably because most larvae were already fully developed and were overwintering as prepupae.

The higher *A. planipennis* emergence densities from logs that were tarped in both the shade and full sun (Table 4) were likely linked to the high relative humidity maintained by these storage treatments (Table 8). In addition, tarped logs were protected from minimum temperature extremes (Table 6). It is interesting that emergence density did not vary significantly between the full sun and shade storage treatments in either year of the study. Perhaps, even when in full sunlight, interior logs were still mostly shaded, and therefore the full sun treatment actually differed little from logs kept in the shade. In addition, perhaps *A. planipennis* survival in the full sun and tarped treatment would have been lower if we had used a clear tarp, which resulted in higher maximum temperatures compared with blue or black tarps (Table 7). Tarping logs in full sun with clear plastic has been shown to significantly reduce survival of bark beetles (Scolytidae) in infested logs compared with untarped logs (Buffam and Lucht 1968, Sanborn 1996).

In conclusion, survival and adult size of *A. planipennis* was significantly reduced when trees were cut early during larval development, i.e., during July or August in southern Michigan. Splitting logs and storing them untarped in full sun or shade further reduced adult emergence density. Although some of the firewood treatments we tested were very effective in reducing adult emergence density, none of the treatments were 100% effective in preventing adult emergence. Further studies should investigate *A. planipennis* survival under different tarp materials that may allow temperatures to reach lethal levels, especially for logs stored in full sun. Our results indicate that if trees are infested at the time of cutting, there is a risk of moving live *A. planipennis* in firewood for at least 1 to 2 yr after cutting.

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